University of Science and Technology

Engineering of electronic

Physics II

COURSE COORDINATOR

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Lecture one

Coulomb's Law and Electric Fields

Coulomb's Law and Electric Fields

COULOMB'S LAW: Suppose that two point charges, q and q', are a distance r apart in vacuum. If q and q' have the same sign, the two charges repel each other; if they have opposite signs, they attract each other. The force experienced by either charge due to the other is called a *Coulomb* or *electric force* and it is given by *Coulomb's Law*,

$$F_E = k\frac{qq'}{r^2} \quad \text{(in vacuum)}$$

As always in the SI, distances are measured in meters, and forces in newtons. The SI unit for charge q is the *coulomb* (C). The constant k in Coulomb's Law has the value

$$k = 8.988 \times 10^9 \ \mathrm{N \cdot m^2/C^2}$$

which we shall usually approximate as $9.0 \times 10^9 \ \mathrm{N \cdot m^2/C^2}$. Often, k is replaced by $1/4\pi\epsilon_0$, where $\epsilon_0 = 8.85 \times 10^{-12} \ \mathrm{C^2/N \cdot m^2}$ is called the *permittivity of free space*. Then Coulomb's Law becomes,

$$F_E = \frac{1}{4\pi\epsilon_0} \frac{qq'}{r^2} \qquad \text{(in vacuum)}$$

When the surrounding medium is not a vacuum, forces caused by induced charges in the material reduce the force between point charges. If the material has a *dielectric constant* K, then ϵ_0 in Coulomb's Law must be replaced by $K\epsilon_0 = \epsilon$, where ϵ is called the *permittivity of the material*. Then

$$F_E = \frac{1}{4\pi\epsilon}\frac{qq'}{r^2} = \frac{k}{K}\frac{qq'}{r^2}$$

For vacuum, $K = 1$; for air, $K = 1.0006$.

Coulomb's Law also applies to uniform spherical shells or spheres of charge. In that case, r, the distance between the centers of the spheres, must be larger than the sum of the radii of the spheres.

AN ELECTRIC FIELD is said to exist at any point in space when a test charge, placed at that point, experiences an electrical force. The direction of the electric field at a point is the same as the direction of the force experienced by a *positive* test charge placed at the point.

Electric field lines can be used to sketch electric fields. The line through a point has the same direction at that point as the electric field. Where the field lines are closest together, the electric field is largest. Field lines come out of positive charges (because a positive charge repels a positive test charge) and come into negative charges (because they attract the positive test charge).

THE STRENGTH OF THE ELECTRIC FIELD ($\vec{\mathbf{E}}$) at a point is equal to the force experienced by a unit positive test charge placed at that point. Because the electric field strength is a force per unit charge, it is a vector quantity. The units of $\vec{\mathbf{E}}$ are N/C or V/m.

If a charge q is placed at a point where the electric field due to other charges is $\vec{\mathbf{E}}$, the charge will experience a force $\vec{\mathbf{F}}_E$ given by

$$\vec{\mathbf{F}}_E = q\vec{\mathbf{E}}$$

If q is negative, $\vec{\mathbf{F}}_E$ will be opposite in direction to $\vec{\mathbf{E}}$.

ELECTRIC FIELD DUE TO A POINT CHARGE: To find E (the signed magnitude of $\vec{\mathrm{E}}$) due to a point charge q, we make use of Coulomb's Law. If a point charge q' is placed at a distance r from the charge q, it will experience a force

$$F_E = \frac{1}{4\pi\epsilon}\frac{qq'}{r^2} = q'\left(\frac{1}{4\pi\epsilon}\frac{q}{r^2}\right)$$

But if a point charge q' is placed at a position where the electric field is E, then the force on q' is

$$F_E = q'E$$

Comparing these two expressions for F_E, we see that

$$E = \frac{1}{4\pi\epsilon}\frac{q}{r^2}$$

This is the electric field at a distance r from a point charge q. The same relation applies at points outside a finite spherical charge q. For q positive, E is positive and $\vec{\mathrm{E}}$ is directed radially outward from q; for q negative, E is negative and $\vec{\mathrm{E}}$ is directed radially inward.

Solved Problems

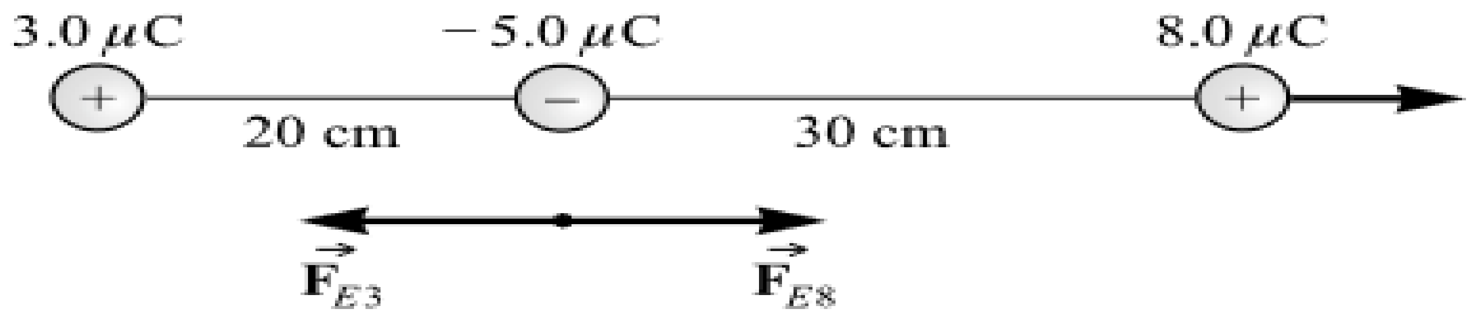
Two coins lie 1.5 m apart on a table. They carry identical charges. Approximately how large is the charge on each if a coin experiences a force of 2 N?

$F_E = (k/K)q_1q_2/r^2$, gives (with K approximated as 1.00)

$$q_1q_2 = q^2 = \frac{F_E r^2}{k} = \frac{(2\ \mathrm{N})(1.5\ \mathrm{m})^2}{9 \times 10^9\ \mathrm{N{\cdot}m^2/C^2}} = 5 \times 10^{-10}\ \mathrm{C}^2$$

from which $q = 2 \times 10^{-5}$ C.

Three point charges are placed on the x-axis as shown in Fig. 24-1. Find the net force on the $-5\ \mu C$ charge due to the two other charges.



$$F_{E3} = (9.0 \times 10^9\ \mathrm{N \cdot m^2/C^2}) \frac{(3.0 \times 10^{-6}\ \mathrm{C})(5.0 \times 10^{-6}\ \mathrm{C})}{(0.20\ \mathrm{m})^2} = 3.4\ \mathrm{N}$$

$$F_{E8} = (9.0 \times 10^9\ \mathrm{N \cdot m^2/C^2}) \frac{(8.0 \times 10^{-6}\ \mathrm{C})(5.0 \times 10^{-6}\ \mathrm{C})}{(0.30\ \mathrm{m})^2} = 4.0\ \mathrm{N}$$

From the diagram, the resultant force on the center charge is

$$F_E = F_{E8} - F_{E3} = 4.0\ \mathrm{N} - 3.4\ \mathrm{N} = 0.6\ \mathrm{N}$$

and it is in the $+x$-direction.

Compute (*a*) the electric field E in air at a distance of 30 cm from a point charge $q_1 = 5.0 \times 10^{-9}$ C, (*b*) the force on a charge $q_2 = 4.0 \times 10^{-10}$ C placed 30 cm from q_1, and (*c*) the force on a charge $q_3 = -4.0 \times 10^{-10}$ C placed 30 cm from q_1 (in the absence of q_2).

(*a*)

$$E = k\frac{q_1}{r^2} = (9.0 \times 10^9\ \mathrm{N \cdot m^2/C^2})\frac{5.0 \times 10^{-9}\ \mathrm{C}}{(0.30\ \mathrm{m})^2} = 0.50\ \mathrm{kN/C}$$

directed away from q_1.

(*b*)

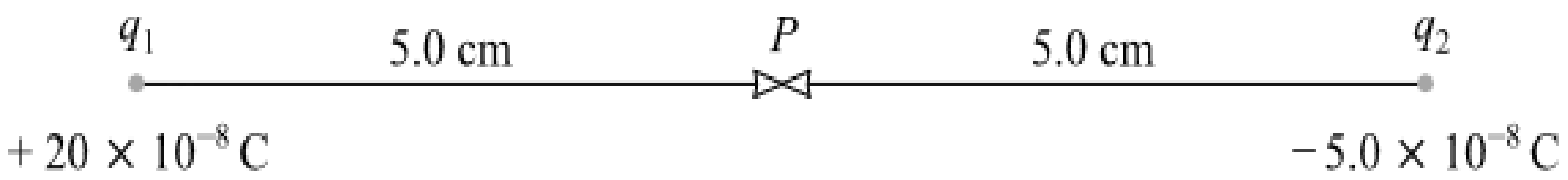
$$F_E = Eq_2 = (500\ \mathrm{N/C})(4.0 \times 10^{-10}\ \mathrm{C}) = 2.0 \times 10^{-7}\ \mathrm{N} = 0.20\ \mu\mathrm{N}$$

directed away from q_1.

(*c*)

$$F_E = Eq_3 = (500\ \mathrm{N/C})(-4.0 \times 10^{-10}\ \mathrm{C}) = -0.20\ \mu\mathrm{N}$$

For the situation shown in Fig. 24-5, find (*a*) the electric field E at point P, (*b*) the force on a -4.0×10^{-8} C charge placed at P.



$$E = E_1 + E_2 = k\frac{|q_1|}{r_1^2} + k\frac{|q_2|}{r_2^2} = \frac{k}{r_1^2}(|q_1| + |q_2|)$$

where $r_1 = r_2 = 0.05$ m, and $|q_1|$ and $|q_2|$ are the absolute values of q_1 and q_2. Hence,

$$E = \frac{9.0 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2}{(0.050\ \text{m})^2}(25 \times 10^{-8}\ \text{C}) = 9.0 \times 10^5\ \text{N/C}$$

(*b*) A charge q placed at P will experience a force Eq. Therefore,

$$F_E = Eq = (9.0 \times 10^5\ \text{N/C})(-4.0 \times 10^{-8}\ \text{C}) = -0.036\ \text{N}$$

Supplementary Problems

If two equal charges, each of 1 C, were separated in air by a distance of 1 km, what would be the force between them? *Ans.* 9 kN repulsion

Determine the force between two free electrons spaced 1.0 angstrom (10^{-10} m) apart. *Ans.* 23 nN repulsion

What is the force of repulsion between two argon nuclei that are separated by 1.0 nm (10^{-9} m)? The charge on an argon nucleus is $+18e$. *Ans.* 75 nN

Two equally charged balls are 3 cm apart in air and repel each other with a force of 40 μN. Compute the charge on each ball. *Ans.* 2 nC

Three point charges are placed at the following points on the x-axis: $+2.0\,\mu C$ at $x = 0$, $-3.0\,\mu C$ at $x = 40$ cm, $-5.0\,\mu C$ at $x = 120$ cm. Find the force (*a*) on the $-3.0\,\mu C$ charge, (*b*) on the $-5.0\,\mu C$ charge. *Ans.* (*a*) -0.55 N; (*b*) 0.15 N

A point charge of -3.0×10^{-5} C is placed at the origin of coordinates. Find the electric field at the point $x = 5.0$ m on the x-axis. *Ans.* 11 kN/C in $-x$-direction